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THE THEORY OF UNM- ED GASES

Ya. B. Zel'dovich

[Digest]

This article discusses the reaction of fuel and oxygen accompanied by combustion products and heat, and considers the steady state with continuous supply of reactants and removal of products. This state is characterized by the fact that fuel and oxygen, or air, are supplied separately, i.e., are not mixed preliminarily. Therefore, for large values of the constant describing the speed of reaction of oxygen with fuel, the combustion does not exceed some definite intensity, this limit depending upon the speed of mixing of fuel and oxygen.

Combustion, itself, is noted to change substantially the concentration distribution in comparison with that of the same gases mixed without combustion. The author accepts the long-established basic quantitative representation of the flame surface as separating the region of oxygen, but no fuel (oxidizing region) from the region of fuel but no oxygen (reduction region).

Burke and Schumann calculated the form of the flame surface in the very special case of combustion in parallel concentric laminar flows of fuel and oxygen or air. However, they did not consider in detail the phenomena occuring in the flame zone. Shvab's work is more complete.

In his recently published work, completed in 1940 in Leningrad, Shvab considered in detail the problem of supply in a turbulent jet of flame, both for a pure combustible gas and for a gas mixture with an insufficient quantity of air. Shvab found relations among concentration of gas, oxygen and combustion products, temperature and gas velo-ity. A number of Shvab's results (in particular, the constancy of the concentration of combustion products and temperature) for the flame surface were included in this article for completeness of the exposition.

The detailed consideration of the zones and kinetics of reaction is essentially new.

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This study clarified the maximum possible intensities of combustion for laminar flow. This maximum intensity is limited by the insufficient speed of reaction, even when the fuel and oxygen are supplied at high speed to the flame surface.

In the mathematical treatment of the subject, the general equations of gas flow for arbitrary temperatures, diffusion coefficients, heat conductivities, etc., are developed. These equations are analyzed and, finally, equations describing the state of the flame surface are developed; the distribution of reaction products and the temperature is then calculated. The last calculation shows that, in rapid combustion of unmixed gases in the reaction zone, exactly the same concentration of the combustion products is obtained as if the burning gases were mixed in stoichiometric proportion and the combustion reaction carried out without any diffusion space.

In precisely the same way, if there are no heat losses by radiation and no cooling surfaces in the flame and if the coefficients of temperature conductivity and diffusion are equal, then the temperature of the diffusion flame in the combustion zone can be shown to equal identically the temperature of combustion of stoichiometric mixture of the given gases under constant pressure.

The conclusion that the temperature of unmixed flame is equal to the temperature of combustion of a stoichiometric mixture is in apparent contradiction with experiment. In experiment, however, the condition specified in the above conclusion is not fulfilled, namely, that no heat be lost from radiation or cooling surfaces in the flame. The quantity of heat given off by radiation cannot be disregarded in the heat balance of a laboratory burner.

These considerations are used to calculate the status of the flame surface for the supply of any quantity of gas and air for any gas of low caloric value; this calculation is based on the assumption of high speeds of chemical reaction at the flame surface (even for the combustion temperature), which in turn reduces the thickness of the reaction zone so that it may be considered as a geometrical surface of null thickness.

A different picture follows for low speeds of reaction. By analogies with other phenomena in combustion and explosion, apparently a decrease in reaction speed (all other conditions being equal) will at first cause a certain quantitative variation, namely an expansion of the reaction zone, and then after attainment of a certain critical value the flame will be extinguished, combustion will become impossible and stop, and the old gas and air will merely mix without reaction instead of burning. These critical conditions of extinction are then considered in the simplest, schematicized case.

The calculations which follow permit one to determine the possible limits of intensities for the combustion of unmixed gases which is dependent upon the limiting speed of chemical reaction. In order of magnitude, this limit is close to the combustion speed of a stoichiometric mixture. The limit found helps to explain at least qualitatively the fact that, in the flow of a fast jet from a pipe, the flame is generally located at a certain distance from the discharge section of the pipe since the flame is disrupted at the outlet where the mixing of the reacting components is most intense.

The practical and important case concerning the limits of intensities of turbulent combustion of unmixed gases was not considered in the work because of its complexity. This complexity is linked with the fact that the average speed of reaction cannot be related to the average temperature under turbulent conditions.

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